S-N curve fatigue study and the stress-strain properties on the refurbish NITI SMA for reinforcing bar in concrete

To cite this article: Nubailah Abd. Hamid *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **469** 012116

IOP Conf. Series: Materials Science and Engineering 469 (2019) 012116 doi:10.1088/1757-899X/469/1/012116

S-N curve fatigue study and the stress-strain properties on the refurbish NITI SMA for reinforcing bar in concrete

Nubailah Abd.Hamid[1], Azmi Ibrahim [1], Azlan Adnan[2]

[1]Faculty of Civil Engineering, Department of Civil Engineering, Universiti Teknologi Mara, 40450 Shah Alam, Malaysia.
[2]Faculty of Civil Engineering, Department of Civil Engineering, Universiti Teknologi Malaysia, 81310 Skudai Universiti Teknologi Malaysia.

Corresponding author: nubailah_hamid@yahoo.com

Abstract. The earthquake load in structures is assumed as a low-cycle loading type load in structures that may cause low-cycle fatigue in earthquake resisting structures. Hence**,** this paper is to highlight and compare the fatigue properties of refurbish pseudoelastic shape memory alloy (SMA) and structural steel for used as seismic reinforcement features in concrete structures. This experiment study on the stress (S) against the number of cycles to failure (N) known as an S-N curve were conducted using INSTRON 8801 Servo hydraulic Fatigue Testing System with 3Hz of loading frequency with the stress varies between $0.9F_{yield}$ and $1.45F_{yield}$ for 8 SMA samples and 2 steel samples with stress varies of $0.64F_{yield}$ and $1.15F_{yield}$. Two type of SMA samples were used including three 12.7mm SMA samples with A_f-25, 6 SMA samples with A_f-6.3 with 12 mm diameter respectively. As a result, the structural steel were observed could with stand approximately 93710 cycles before failure if loaded up to its yield stress, while SMA of diameter 12.7mm can withstand until 19040.75 cycles. Type 1 of refurbish SMA rebar that were reused shows a much better behaviour against fatigue than structural steel rebar and is more reliable in seismic periodic loads. However, for second type refurbish and reused of SMA shows the vice versa and can only sustain maximum 23674.25 cycles.

1. Introduction

SMA is a functional material that gain increasing interest in numerous study and feasibility application for civil engineering due to two distinctive properties that can recover their original shape either by the stress-induced after undergoing large deformations (superelastic effect) or heat-induced (shape memory effect) [1]. This smart material can be exploited base on their classification on the reversible phase transformations between these two solid phases.

The use of superelastic SMA for seismic resistant design is due to their advantageous properties such as excellent self-centering ability, energy dissipation capacity, high fatigue, corrosion resistance and superelastic properties. In order to control the quality of the material, it is vital to experimentally study the mechanical properties of the material and fatigue test to ensure that the fatigue life of material is greater than required and safe for the service life anticipated. This is because; the repetitive loading of the material will causes degradation due to the accumulation of damage in material that can cause a major fatality to human life and cost due to fatigue failure.

The progressive, localized structural damage that occurs when a material is subjected to cyclic loading and the corresponding number of load cycles or the time during which the member is subjected to the loads before fracture or crack occurs is referred to as the fatigue life. While the fatigue testing are used to establish the materials resistance to repetitive loading and the data are often normalized with respect to the static strength value obtain from tensile testing.

There have been a large number of researcher studies the material properties and the fatigue study of the superelastic NiTi. Youngsik (2002), investigate the effect of the alloy compositions on the cyclic bending fatigue behaviors of the Ti–Ni base shape memory alloy wires [1]. Casciati and Alessandro (2009), focused on the Cu-based alloy bars to do experimental studies on the fatigue characteristics at given temperatures were investigated [2]. M Sherif and Ozbulut (2017), investigated the tensile response and functional fatigue characteristics of a NiTi shape memory alloy (SMA) cable with an outer diameter of 5.5 mm.

The results of the tensile tests revealed that the SMA cable exhibits good superelastic behavior up to 10% strain. Fatigue characteristics were investigated under strain amplitudes ranging from 3% to 7% and a minimum of 2500 loading cycles. Functional fatigue test results indicated a very high superelastic fatigue life cycle for the tested NiTi SMA cable [3]. G. Eggeler et al present the paper considers structural and functional fatigue of 1.0, 1.2 and 1.4mm diameter of NiTi shape memory alloys, discusses on how microstructures can be optimized to provide good fatigue resistance and the stress–strain hysteresis in low cycle pull–pull fatigue of pseudo-elastic NiTi wires [4]. Ying Zhao et al (2005) examined the compression behaviour of the porous NiTi where the model of the macroscopic compression behaviour of porous SMA were established [5].

Shrestha et al [6] analyzed the functional fatigue of polycrystalline and single-crystal CuAlMn superelastic SMAs with a diameter of 5 mm. The Cu-based SMA bars were subjected to 1000 loading cycles under 6% and 7% strains. Isalgue et al [7] conducted tensile testing on 2.46mm diameter NiTi superelastic wires subjected to a loading strain of 8% for 100 loading cycles to assess the variation in hysteretic response.

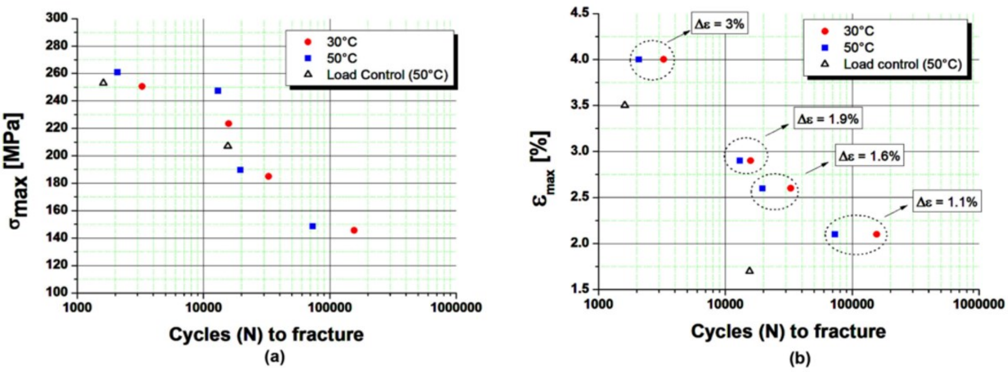
However, limited study have been investigated for the superelastic fatigue of SMA materials especially on the recycle or reusable superelastic NiTi as reinforcing elements for seismic resiliency. Although these studies highlighted the advantageous characteristics of SMA bar such as good superelastic response and fatigue resistance, functional fatigue of reused NiTi bar has yet to be investigated.

Hence, this paper is to investigate the fatigue properties response and compare the mechanical properties of the Ni of the on tensile and compressive behaviour with the structural steel for use as reinforforcing element as seismic resisting structure. Three SMA bar with different Austenite temperature (A_f) and diameter were evaluated their properties with 0.25050 mm/min strain rate using the INSTRON 8801 Fatigue Machine.

2. Fatigue Test (S-N Curves)

According to Casciati, et al. (2008) [7] the adoption of SMA structural elements in any civil engineering application requires that the material has a fatigue lifetime of at least 1000 working cycles. Generally, there are two types of frequent loads affecting structures. Loads with high frequencies or multiple repeat cause high-cycle fatigue, such as in bridges and marine structures or machines, but earthquake load in structures is assumed as a low-cycle loading type and may cause low-cycle fatigue in earthquake resisting structures.[9]

Figure 1 shows the result obtained from the experimental study by Shrestha et al, (2016) [6] to evaluate the fatigue lifetime of the Cu-based alloy, and to its potential improvement by performing a proper ageing and an adequate mechanical training.



IOP Conf. Series: Materials Science and Engineering 469 (2019) 012116 doi:10.1088/1757-899X/469/1/012116

Figure 1. Completely reversed sinusoidal wave form

2.1 Fatigue test data presentation

It is essential to do fatigue test to ensure that the fatigue life of material is greater than required and safe for the intended service life. Fatigue testing are used to establish the resistance of composite materials to repetitive loading and the data are often normalized with respect to the static strength value obtain from tensile testing.

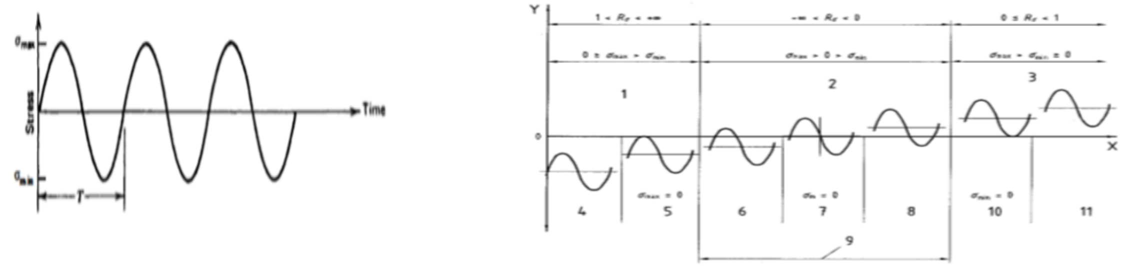


Figure 2. Completely reversed sinusoidal wave form

In fatigue testing, the results are normally expressed by plotting stresses or strain versus number of cycles to failure (Figure 2). This method of representation leads to well-known S-N plot or Wohler curve. It shows the degrading in fatigue strength and it will lead to the damage mechanism.

The Typical cycles (N) to fracture (S-N curve data diagram) is shown in the Figure 3 while the Fatigue S-N curve for Nitinol and mild steel as represented in the Figure 4.

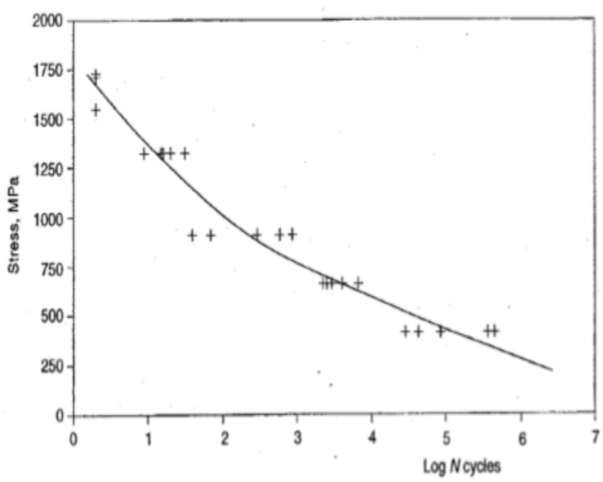


Figure 3. Typical Cycles (N) to fracture (S-N curve fatigue data diagram)

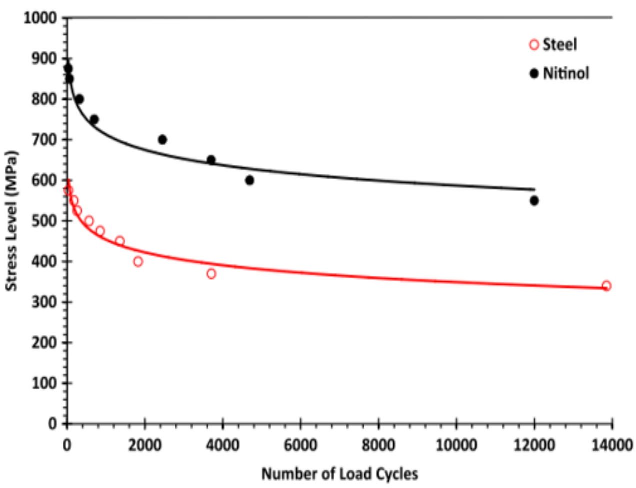


Figure 4. Fatigue S-N curve for Nitinol and mild steel

2.2 Methodology S-N curve calculation

The calculation of stress equation , stress ratio equation, stress range equation, stress mean equation, mean stress equation, stress amplitude equation and the alternating stress amplitude as shown in the equation below.

i. The stress equation

$$\sigma = \frac{F}{A} \qquad (1)$$

IOP Conf. Series: Materials Science and Engineering 469 (2019) 012116 doi:10.1088/1757-899X/469/1/012116

ii. The stress ratio equation

$$R = \frac{\sigma_{\min}}{\sigma_{\max}} \tag{2}$$

iii The stress range equation

$$\Delta_{\sigma} = \sigma_{\max} - \sigma_{\min} \tag{3}$$

iv The mean stress equation

$$\sigma_m = \frac{\sigma_{\max} - \sigma_{\min}}{2} \tag{4}$$

3. Experiment Method

Comparative study of the mechanical properties of shape memory alloy and structural steel for use in seismic resisting structures is the goal of this research. Generally, there are two types of frequent loads affecting structures. Loads with high frequencies or multiple repeat cause high-cycle fatigue, such as in bridges and marine structures or machines, but earthquake load in structures is assumed as a low-cycle loading type and may cause low-cycle fatigue in earthquake resisting structures.

In order to compare the fatigue property of the refurbish SMAs, the fatigue tests was conducted on the nominal stress required to cause a fatigue failure in some number of cycles, which produces a plot of stress (S) against the number of cycles to failure (N) known as an S-N curve using the 250 kN INSTRON 8801 Fatigue Machine. The specimens were subjected to repetitive load by using Wavematric software available in the INSTRON 8801 Servohydraulic Fatigue Testing System as shown in the Figure 5.

The specimen is set with hydraulic grips on INSTRON fatigue machine during the fatigue test process as shown in Figure 6. The tests are conducted on steel and Nitinol using standard tension-compression samples similar to cyclic samples. For structural steel, the stress varies between $0.64F_{yield}$ and $1.15F_{yield}$ for 2 samples while for Nitinol, the stress varies between $0.64F_{yield}$, $0.9F_{yield}$ and $1.45F_{yield}$ for 9 samples. The loading frequency is assumed to be 3 Hz. Figure 4 shows the S-N curve for structural steel and Nitinol. The fatigue loading is displayed during the fatigue test as shown in Figure 2.

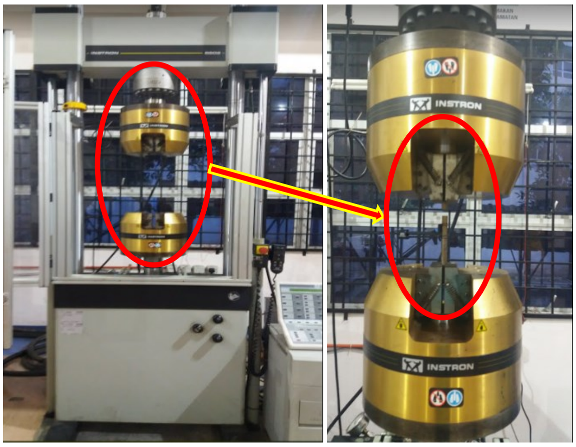


Figure 5. INSTRON 8801 Servo hydraulic Fatigue Testing System

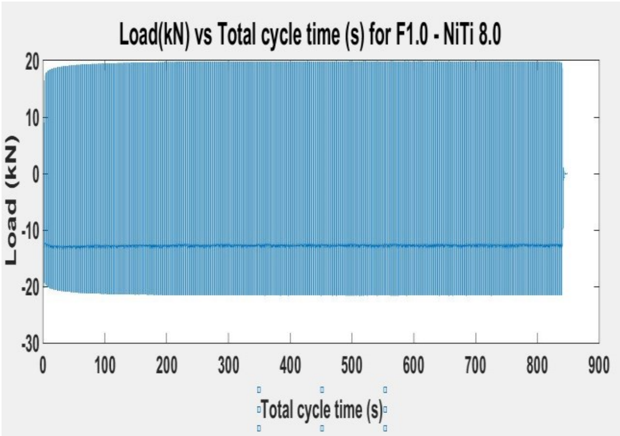


Figure 6. Illustration of Fluctuating Fatigue Loading of Fatigue Test

4. Experiment Result

Recent work has focused on the fatigue properties associates with their performance. There are seven specimens were tested on the fatigue testing. The results obtained for the fatigue life cycle of refurbish NiTi and mild steel as tabulated in Table 1. In this study, the specimens were tested at a high peak stress, where the failure is expected to fail after it reached the yield stress in number of cycles. Table 1 shows the number of fatigue life cycle test for both mild steel rebar and reused NiTi specimens with differences parameters that are required before starting the fatigue test on the specimens which is the load factor, fatigue loading (kN) and the stress level to be input in the Wavematrix Instron software. There are nine specimens which undergone the fatigue testing and the result for all each specimen were successfully obtained and discussed.

Table 1. Comparison of Fatigue life cycle for refurbish NiTi and mild steel

Sample	percentage F(%)	factor	load(kN)	load(kN)	stress level	number load of cycles
Sample 1	Mild steel 10 mm (a)	1.15	1.00	56.191	56.191	1158
Sample 2	Mild steel 10 mm (b)	0.64	0.64	56.191	35.962	93710
Sample 3	NiTi 12.7 -reshape(a)	0.9	0.9	21.308	19.178	6496
Sample 4	NiTi 12.7 AT(b)	1.45	1.45	21.308	30.897	19040.75
Sample 5	NiTi 12.7 AT(c)	0.64	0.64	21.308	13.637	157725.25
Sample 5	NiTi 12.0 AT(a)	0.9	0.9	61.085	54.977	8747
Sample 6	NiTi 12.0 AT(b)	1.45	1.45	61.085	88.573	21.75
Sample 7	NiTi 12.0 AT(c)	0.64	0.64	61.085	39.094	23674.25
Sample 8	NiTi 8 AT (a)	1.15	1.00	24.21	24.21	848
Sample 9	NiTi 8 AT (b)	1.45	1.45	24.21	35.105	442.5
Sample 10	NiTi 8 AT (c)	0.64	0.64	24.21	15.494	17144.5

Figure 7 shows the S-N curve for maximum stresses (MPa) vs cycles to fracture. The result shows that the structural steel show the maximum fatigue threshold at 56.19. While reused NiTi, show the maximum threshold at 88.573, 35.105 and 30.897 for 12mm, 8mm and 12.7 of NiTi respectively. Taking only low-cycle fatigue into account regarding earthquake loads, structural steel will stand approximately 500 cycles before failure if loaded up to its yield stress, whereas Nitinol will stand for 4,700 cycles. On the other hand, structural steel will fail after 40 cycles if loaded up to 1.15Fyield, whereas Nitinol should be loaded up to 1.45 of its yield stress to fail after 40 cycles. Generally, Nitinol shows a much better behavior against fatigue than structural steel and is more reliable in seismic periodic loads.

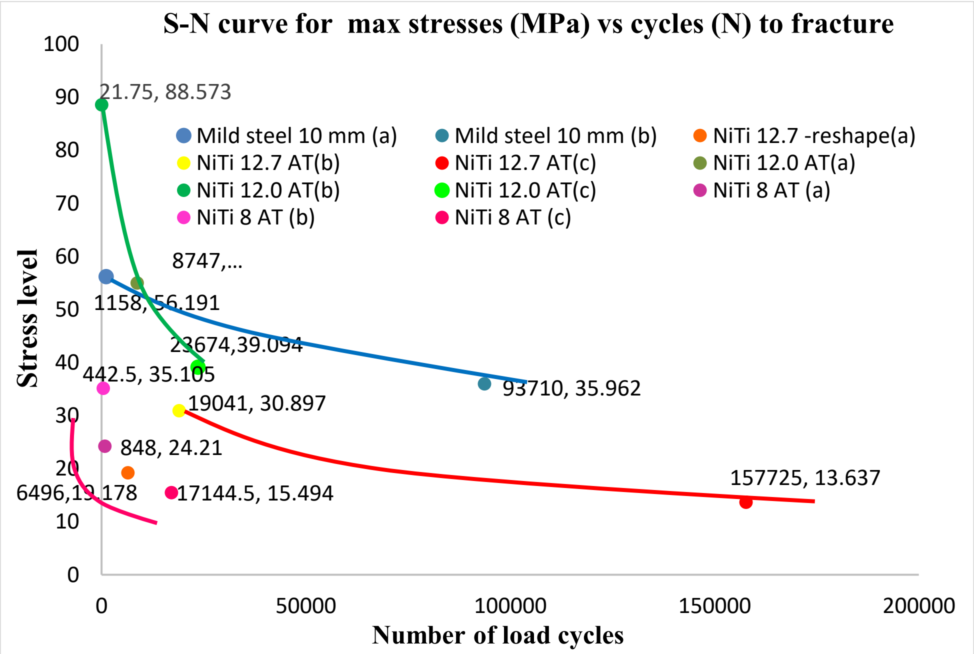


Figure 7. S-N curve for maximum stresses (MPa) vs cycles to fracture.

5. Conclusions and Recommendations

The objective of this study is to assess the fatigue test of reused Ni-Ti alloy in structural engineering and to compare its mechanical properties with structural steel according to experimental results. The following conclusions are drawn based on the results and observations presented in this study:

(a) Reused Nitinol 12.7 mm shows a much better behavior against fatigue than structural steel and is more reliable in seismic periodic loads.

(b) Fatigue life of NiTi 12.7 mm is the most quite satisfactory which can sustain until 157725 cycles which is greater than mild steel.
(c) Fatigue characteristics were investigated under stress level ranging from 13% to 88.573% with aminimum of 442.5 loading cycles.
(d) Functional fatigue test results indicated a very high superelastic fatigue life cycle for the tested reused NiTi bar 12.7 mm. However, the stress level of reused NiTi of 8mm and 12mm were resulted high stress level but less sustain in fatigue life. Both are inot recommended to use for seismic mitigation in this case due to their change in phase transformation but can be heat treated to increase their fatigue life cycle

Acknowledgments

The authors of this work would like to express their sincere gratitude to Universiti Teknologi MARA (UiTM), Universiti Teknologi Malaysia (UTM), KPM and FRGS grant for facilitating the research grant and facilities.

References

[1] Y. Kim, “Fatigue Properties of the Ti-Ni Base Shape Memory Alloy Wire,” *Mater. Trans.*, vol. 43, no. 7, pp. 1703–1706, 2002.
[2] S. Casciati and A. Marzi, “Experimental studies on the fatigue life of shape memory alloy bars,” *Smart Struct. Syst.*, vol. 6, no. 1, pp. 73–85, 2010.
[3] M. M. Sherif and O. E. Ozbulut, “Tensile and superelastic fatigue characterization of NiTi shape memory cables,” *Smart Mater. Struct.*, vol. 27, no. 1, 2018.
[4] G. Eggeler, E. Hornbogen, a. Yawny, a. Heckmann, and M. Wagner, “Structural and functional fatigue of NiTi shape memory alloys,” *Mater. Sci. Eng. A*, vol. 378, no. 1–2, pp. 24–33, Jul. 2004.
[5] Y. Zhao, M. Taya, Y. Kang, and A. Kawasaki, “Compression behavior of porous NiTi shape memory alloy,” *Acta Mater.*, vol. 53, no. 2, pp. 337–343, 2005.
[6] Shrestha K C, Araki Y, Kusama T and Omori T 2016 Functional fatigue of polycrystalline Cu-Al-Mn Superelastic alloy bars under cyclic tension J. Mater. Civil Eng. 28 0401519
[7] Casciati , F., Faravelli, L., Isalgue, A., Martorell, F., Soul, H. and Torra, V. (2008), “SMA fatigue in civil engineering applications”, Adv. Sci. Technol., Trans Tech Publications, Switzerland, 59, 168-177.
[8] A. Jalaeefar and B. Asgarian, “Experimental Investigation of Mechanical Properties of Nitinol, Structural Steel and Their Hybrid Component,” *J. Mater. Civ. Eng.*, vol. 9, no. October, p. 121001063047003, 2012.